Investigation the effect of aggregate on the performance of permeable concrete

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ABSTRACT: Presently natural resources are increasingly consumed due to rapid urbanization, so that various strategies are being investigated by engineers to protect and restore natural ecosystems all over the world. Permeable pavement, due to its high porosity and permeability, is considered as an alternative to traditional impervious hard pavements for the sake of controlling stormwater in an economical and friendly environmental way. Concrete as a construction material has been used in pavement surfaces since 1865 and during the past 20 years, permeable concrete developed into a subset of the broader family of pervious pavements. It is normally made of single sized aggregate bound together by Portland cement. Considering about influences of aggregate properties in the concrete compositions, different aggregate types and sizes were tried and their effects on the compressive strength and permeability of permeable concrete were investigated. The optimum aggregate for pervious concrete is consequently recommended.

1 INTRODUCTION

1.1 *Permeable Pavement*

Presently natural resources are increasingly consumed due to rapid urbanization and thereafter human construction activities, so that various strategies are being investigated by engineers to protect and restore natural ecosystems all over the world. Permeable (porous/pervious) pavement is termed as comprising materials that facilitate stormwater infiltrate and transfer to the underlying subsoil (ARMCANZ&ANZECC 2000). With sub-structure which stores water underground temporarily, it is called permeable pavement system. Instead of installing rainfall detention ponds or soakaways, this new system is more cost effective compared to the traditional impervious pavement. Meanwhile, it has been acknowledged by many researchers that permeable pavement system is capable of reducing the sediments and contaminants for lessening the pollutant loads on stormwater, thus it is considered as an economic and environmental-friendly construction as a part of city drainage system.

In Australia, permeable pavement has been utilized as a potential tool of Water Sensitive Urban Design (WSUD) to manage natural water. From 1994 the University of New South Wales (UNSW) started to research into permeable concrete paving and more recently the University of South Australia (UniSA) is also involved. However, the previous studies conducted both in UNSW and UniSA mainly concentrated on water quality and pollution control through permeable pavements and, only the properties of basecourse materials in permeable pavement system and segmental paving have been studied. There is still a gap of optimizing the surface materials for permeable pavements.

1.2 *Permeable concrete pavement*

The materials used for permeable pavement are classified into nine categories (Ferguson 2005): porous aggregate, porous turf, plastic geocells, open-jointed paving blocks, open-celled paving grids, porous concrete, porous asphalt, soft paving materials, and decks. Concrete has been used in pavement surfaces since 1865, when dense concrete street pavements were first experimentally installed in Scotland (Croney 1997). Porous concrete was first used in pavements during World War II. As a subset of the broader family of permeable pavements, porous concrete is also referred to as permeable concrete, enhanced porosity concrete, or Portland cement pervious pavement. It is normally made of single–sized aggregate bound together by Portland cement, physically and chemically identical to dense concrete (Ferguson 2005).

Permeable concrete is relatively porous, providing by the omission of fine aggregates (Scholz & Grabowiecki 2007) and filled most of volume with coarse aggregate, thus, porous concrete obtains more voids in the structure leading to good water infiltration and air exchange rates. Permeable concrete typically has a void content of 15-25% compared to 3-5% for conventional pavements according to the Interlocking Concrete Pavement Institute (ICPI 2007). Comparing with porous asphalt, permeable concrete exhibits some advantages in pavement projects. For instance, porous concrete has a better capacity of keeping high porosity in hot weather (ICPI 2007), which is more suitable for Australia's climate. Nonetheless, the compressive strength and flexural strength are sufficient for low volume traffic areas but not for heavy traffic loading roads (Ferguson 2005). Currently they are mainly used in carparks, footpaths and bicycle trails. This study aims to improve the strength of porous concrete without losing permeability so that it could be adoptable for supporting higher volume traffic.

2 LITERATURE REVIEW

It has been generally accepted that the strength of concrete is influenced by many factors, such as the amount and type of cement, aggregate, water to cement ratio, chemical additives and curing conditions. From the view of composite structure, Larrard & Belloc (1997) pointed out the strength of concrete was indeed determined by the properties of mortar, coarse aggregate and the interface. For normal concrete, previous researches have revealed the effects of aggregates on strength with different aggregate type, size and gradation. However, these conclusions for normal concrete cannot be simply extended to permeable concrete, since porous concrete typically does not contain fine aggregate to fill the voids, only relying on cement paste to bond graded coarse aggregate together. Research of pervious concrete has ever been conducted at Tennessee Technological University (Crouch et al. 2007). It is indicated that the compressive strength, effective void content and permeability are largely dependent upon the aggregate. Crouch et al. (2007) stated that not only the size of aggregate, but also the gradation and amount of aggregate could affect the compressive strength and static modulus of elasticity on pervious Portland cement concrete. Meininger (1988) used different aggregate sizes (10mm and 19mm) in non-fine concrete study and the results showed that larger aggregate sizes would result in lower compressive strength, which corresponded with the results found from Yang & Jing (2003). It claimed the decrease of aggregate size led to higher pervious concrete strength, resulting from the increase of the interface strength between the aggregate and cement paste (Yang & Jing 2003). Ghafoori and Dutta (1995) also set up the relationship between gravimetric air content and permeability and porosity in no-fines concrete. However, in Australia there has been no published research that reveals the effect of aggregates on the structural performance of pervious concrete. The objective of this paper is to investigate the effect of aggregate on the performance of pervious concrete using locally available materials.

3 EXPERIMENTAL INVESTIGATION

3.1 *Materials*

3.1.1 *Cement*

Normal Portland cement from local supplier was used in each mix design. It exceeds the minimum specification given in AS (Australian Standard) 3972 -1997.

3.1.2 *Aggregate*

Different types of aggregates exhibit different strength, permeability and geometry stability due to different mineral composition, grain sizes, types of formation, texture and location of the aggregates source. Coarse aggregate is mainly used as a primary ingredient in making the previous concrete. Fine aggregates were not added to the mixture in this research. According to Krezel (2006), crushed igneous rocks are more preferable as coarse aggregate for concrete due to their higher strength. However, since the availability of igneous rock in Australia is becoming scarce Krezel (2006), this research diverted to the crushed sedimentary and metamorphic rocks. Three types of coarse aggregate were obtained from local quarry: quartzite, dolomite and limestone. Dolomite was a sedimentary carbonate rock, composed of the mineral dolomite, also contained impurities such as calcite, quartz and feldspar. Dolomite formed in groups of rhombohedral crystals with curved, saddle-like faces. Limestone was also sedimentary rock. Although some limestones were nearly pure calcite, there were often varying amounts of clay, silt and sand. Quartzite was a dense, hard metamorphic rock. The quartzites obtained from local quarry were red due to a large amount of iron oxide. The geology and mechanical properties of aggregate source were tested and given in Table 1.

The proportions of all sample mixtures were designed at aggregate to cement ratio of 4.5 and water to cement ratio of 0.36.

Table 1. Engineering properties of aggregates

Aggregate	Flakiness Index	Mean water absorption	Los Angeles Abrasion Value	Dry strength
	%	%	%	KN
Type A	21	2.8	27	163
Type B	35	0.8	15	225
Type C	15	0.3	38	74

Type A: Quartzite Type B: Dolomite Type C: Limestone

3.2 *Sample preparation and testing methods*

3.2.1 *Sieving*

The preparation of standard concrete test specimens is based on Australian Standards and Guidelines. For mix proportioning purposes, all of the raw 10mm aggregates from quarries were sieved and separated into different groups using standard sieves. Specific gradations were then obtained by recombining small fractions of separated aggregates. The mixed grading of each batch was shown in Table 2.

Table 2. Aggregate size distribution

Sieve size(mm)	16	13.2	9.5	6.7	4.75	2.36	1.18
Mix Number	Passing percentage by mass (%)						
Type A							
A1	100	100	100	0	0	0	0
A2	100	100	100	30	0	0	0
A3	100	100	90	30	0	0	0
Type B							
B1	100	100	100	0	0	0	0
B2	100	100	100	30	0	0	0
B3	100	100	90	30	0	0	0
Type C							
C1	100	100	100	0	0	0	0
C2	100	100	100	30	0	0	0
C3	100	100	90	30	0	0	0

3.2.2 *Casting and compaction*

Before the mixing, aggregates were washed using tap water and dried in oven for one day to clean the silt or crusher dust, in case they prevent the development of good bond between aggregate and cement paste in concrete mixture.

A total of 8 cylinders with 100mm diameter and 200 mm height were cast for each batch to explore the compressive strength and two steel beam moulds were cast when testing the flexure strength.

The compaction method for making porous concrete is one of the most influential factors in the sample preparation. Two compaction methods have been assessed in previous research (Zhuge 2008), one was using compaction hammer and the other was using vibration table. While the hammer compaction packed the aggregate particles together more tightly, the density of porous concrete samples increased with the loss of permeability. As the impaction strength of a falling hammer was so strong to crush the weak aggregate and create weak layers, the vibration method seemed to be more suitable for majority of aggregates, such as limestone and dolomite. However, for the sake of achieving the maximum cohesion between aggregate particles, a combined compaction method was attempted, that was, not only applied the standard rodding compaction method, but also incorporated a static compactor in the consequent vibrating procedure. The frequency of vibration table was controlled at 75Hz. This method allowed the coarse aggregate not deformed under compacting whilst increase the contact surface and alignment of aggregate particles, which was believed a substantial aspect to enhancing the strength of porous concrete.

3.2.3 *Testing*

For compression test, the casted cylinders were demoulded after 24 hours, labeled and weighted. Then the samples were cured in a lime bath at 23±2°C, according to AS 1012.8.1-2000. For each batch, two samples were prepared in permeability testing and others were for compression, three tested at 7 days and 28 days respectively. Sulphur caps were placed on the ends of samples before loading process. The unconfined compressive strengths (UCS) of specimens using different type of aggregates were determined in lab according to AS1012.9-1999.

For flexure test, the moduli of rupture were determined in lab according to AS 1012.11-2000.

For the permeability measurement, test apparatus was improved based on previous research. A cylindrical plastic pipe with inline steel wire and adjustable steel tie fasteners rendered the tubing device tighter to hold up the water leak from the sides of samples (see Fig. 1).

Figure 1. Permeability test rig

Permeability as a unique ability for water to penetrate through the porous concrete was expressed in millimetres per second (mm/s). Since the porous concrete generally own a much higher permeability compared to the normal dense concrete, the permeability test method for the latter one were not still suitable and valid for testing the porous concrete accurately. Thus, the falling head test method was used to determine the permeability of the all the samples and the operation was similar to the falling head test for soil, which complied with AS 1289.6.7.2 -2001.

4 RESULTS AND DISCUSSIONS

4.1 *Compressive strength*

The average compressive strength of porous concrete specimens made with quartzite, dolomite and limestone aggregates at 7 and 28 days were illustrated in Table 3.

Table 3. Compressive strength at different age

Curing time (days)	Compressive strength (MPa)						
	Quartzite		Dolomite			Limestone	
	A1	A2	B1	B2	B3	C1	C2
7	11.6	13.0	15.0	16.0	14.3	14.3	13.5
28	11.8	15.5	15.8	19.0	15.5	15.5	14.0

As it is showed in Table 3, with the identical single-sized aggregate (Group 1), quartzite porous concrete A1 developed the compressive strength of 11.6MPa and 11.8Mpa at 7 and 28 days respectively. Dolomite B1 yielded 15.0MPa and 15.8MPa and Limestone C1 reached 14.3MPa and 15.5MPa. When extending the aggregate size fraction into 4.75mm as described in Table 2, the compressive strength for quartzite and dolomite concrete were both increased (A2 and B2) except for limestone concrete which was slightly decreased (C2).

The porous concrete made with dolomite produced the highest compressive strength among the three types of aggregates. This type of aggregate was further investigated with the size grading varying from 13.2mm to 4.75mm (B3). However, the results indicated that the dolomite concrete with this aggregate gradation (B3) presented a lower strength than that of B1 and B2.

4.2 *Flexural strength*

The average flexural strength (modulus of rupture) of porous concrete specimens made with quartzite, dolomite and limestone aggregates at 7 and 28 days were shown in Table 4.

With the same aggregate grading, dolomite porous concrete yielded the highest flexural strength compared to quartzite and limestone. As indicated in Table 4, it was 1.7MPa and 1.9MPa at 7 and 28 days curing time respectively. In addition, the flexural strength of dolomite B2 was 70% higher than B3 at 7 days and was 60% higher than B3 at 28 days which was similar to the results for compressive strength.

Table 4. Flexural strength at different age

Curing time (days)	Flexural strength (MPa)			
	Quartzite	Dolomite		Limestone
	A3	B2	B3	C3
7	1.5	2.9	1.7	1.5
28	1.6	3.0	1.9	1.5

4.3 *Permeability*

The permeability measurement was conducted after 28 days curing time. The average permeability of porous concrete specimens made with quartzite, dolomite and limestone aggregates were given in Table 5.Three types of aggregates all showed a satisfied permeability, thus there should be a space for the future research to enhancing the strength of porous concrete made with them, because it reflected there were still enough pore voids exiting at this stage.

Table 5. Permeability of porous concrete made with different aggregates at 28 day curing time

Permeability (mm/s)						
Quartzite		Dolomite			Limestone	
A1	A2	B1	B2	B3	C1	C2
27.47	13.67	19.87	8.51	14.78	13.27	15.99

4.4 *Effect of aggregate type*

The results indicated that the type of coarse aggregate used in making porous concrete would influence the strength of porous concrete even though the aggregates were in the same size and gradation. This can be attributed to the different particle shape and texture of different aggregate, as it was shown in Figure 2.

(a) Quartzite

(b) Dolomite

(c) Limestone

Figure 2. Comparison of different aggregate

Because describing the shape of aggregate cannot only rely on vision, the flakiness index of aggregate was conducted according to AS1141.15-1999. As it was shown in Table 1, the dolomite was most flaky and limestone was the least flaky one. It could be regarded as a reason why the aggregate strength of limestone was nearly 30% lower than that of dolomite, but the compressive strength reached around 95% of dolomite (C1 versus B1) without the influence of aggregate size. It was estimated that the more flaky aggregate particles tended to be oriented in one plane under compaction force, which adversely affected the contact area between aggregate and cement, so that the more flaky aggregate did not bond with cement as well as the more rounded aggregate, such as limestone.

4.5 *Effect of aggregate strength*

Comparing the porous concrete samples made with these aggregates, it can be observed that the higher strength of aggregate will result in a higher strength of porous concrete and this effect is the same regardless of whether the porous concrete is under compression or flexure. It is understandable that the strength of porous concrete cannot immensely exceed that of the major part of aggregate particles contained in. Higher strength aggregate, such as dolomite tended to sustain the higher stress than the lower strength aggregate, such as limestone. This property could be used to select aggregates to produce high strength porous concrete.

4.6 *Effect of aggregate size and gradation*

For a certain type of aggregate, take dolomite as an example, the immerged proportion of smaller size aggregate produced the higher strength of porous concrete. It can be seen from Table 3 that when changing from a single sized grading (B1) to a grading varying from 9.5 mm to 4.75mm (B2), the compressive strength of porous concrete increased from 15.0MPa to 16.0MPa at 7 days and from 15.8MPa to 19.0MPa at 28 days. However, when larger sized aggregate was used (B3), although it showed a better gradation, the flexural strength of porous concrete decreased from 2.9MPa to 1.7Mpa at 7 days and from 3.0MPa to 1.9Mpa at 28days when the maximum aggregate size increased from 9.5mm (B2) to 13.2mm (B3). It seemed the flexural strength of porous concrete was more affected than the compressive strength; although the extent of this size influence were not equal for compressive strength and flexural strength, it can be concluded that smaller aggregate size will result in a higher compressive strength and flexural strength, which was consistent with the research of Meininger (1988) and Marolf et al (2004).

Based on the results of permeability (see Table 5), it can be found that the smaller aggregate size will lead to a lower permeability of porous concrete except for that made with limestone. With the same aggregate size gradation, quartzite porous concrete obtained the highest permeability compared to dolomite and limestone porous concrete.

4.7 *Failure mode and bonding*

It was observed that the majority of failures for porous concrete samples intensively took place in the hardened cement paste or the interface between cement and aggregate (see Fig. 3).

Figure 3. Cracked samples of porous concrete

The fractures through the aggregates were less than the kind of former two; this failure was determined by the strength of aggregate. More fractured aggregate particles appeared in the porous concrete made with limestone than that with dolomite or quartzite. However, concrete as a three phase composite material at a microscopic scale included mortar matrix, aggregate and the interfacial transition zone between the two. Although the interfacial transition zone was smaller in proportion compared to mortar matrix and aggregate, its characters influenced the mechanical behaviour of concrete significantly and it was normally regarded as the weakest link in concrete (Prokopski & Halbiniak 2000). On this hand, the porous concrete seemed to perform the same as normal concrete, which corresponded with the research of Bentur (1990). Bentur (1990) also believed there were two weak faces in the interfacial transition zone, the aggregate contact layer and matrix contact layer. On the other hand, there was a little difference between porous concrete and the normal concrete in the mode of fracture. For normal concrete, Zaitsev (1983) pointed out the separation crack occurred first due to the shrinkage of cement matrix and then along the interface of the aggregate and cement paste. Whereas the more fractures developed in the interfacial zone of porous concrete in this study, it could be certified that without fine aggregate, such as sand and any chemical admixture, the bond strength of aggregate and cement in porous concrete was not adequate at this stage and thereafter it became a controlling factor in improving the strength of porous concrete.

4.8 *Effect of other engineering properties of aggregate*

Besides what have been mentioned above, the results in Table 1 also suggested dolomite was more resistant to abrasion for porous concrete, this character should be considered when the porous concrete is expected to use as pavement material in road construction. In addition, despite the quartzite showed a lower flakiness index and a better permeability than dolomite as an aggregate in this research, the clay contamination and impurities such as a large amount of iron oxide covered on the surface of quartzite cannot be omitted, for the purpose of gaining a good development of bond in porous concrete.

5 CONCLUSIONS

The laboratory testing has been carried out to explore the optimum type of aggregate for porous concrete using Australian local quarries. Three most common types of aggregate were applied and the effects of their properties were compared. Along with the study conducted on aggregate size distribution, it can be concluded that the grading of aggregate also need to be controlled in order to achieve the best strength of porous concrete. The preliminary testing results indicated that dolomite might be the proper type of aggregate for porous concrete as a permeable pavement material.

6 REFERENCES

ARMCANZ&ANZECC: Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand 2000.

AS 3972-1997: Portland and blended cements.

AS1012.9-1999: Methods of testing concrete - Determination of the compressive strength of concrete specimens.

AS1141.15-1999: Methods for sampling and testing aggregates - Flakiness index.

AS 1012.8.1-2000: Methods of testing concrete - Method of making and curing concrete - Compression and indirect tensile test specimens.

AS 1012.11-2000: Methods of testing concrete - Determination of the modulus of rupture.

AS 1289.6.7.2 -2001: Methods of testing soils for engineering purposes - Soil strength and consolidation tests - Determination of permeability of a soil - Falling head method for a remoulded specimen.

Bentur, A. 1990. Microstructure interfacial effects and micromechanics of cementitious composites. Ceramic Trans 16: 523-549.

Crouch, P.E. et al. 2007. Aggregate Effects on Pervious Portland cement Concrete Static Modulus of Elasticity. Journal of materials in civil engineering 19(7): 561-568.

Croney, P. & Croney, D. 1997. The design and performance of road pavements. New York: 508.

Ferguson, B.K. 2005. Porous pavements. USA: CRC.

Ghafoori, N. & Dutta, S. 1995. Laboratory investigation of compactee no-fines concrete for paving materials. Journal of materials in civil engineering 7(3): 183-191.

ICPI. 2007. Segmeatal concrete pavement resources for design professionals.

Krezel, Z.A. 2006. Recycled aggregate concrete acoustic barrier. Swinburne University of Technology: http://adt.lib.swin.edu.au/uploads/approved/adt-VSWT20060821.154340/publication

Larrard, F. & Belloc, A. 1997. Influence of aggregate on the compressive strength of normal and high-strength concrete. ACI materials journal 94(5): 26-27.

Meininger, C. 1988. No-fines Pervious Concrete for paving. Concrete International 10(8): 20-27

Marolf, A. et al. 2004. Influence of aggregate size and gradation on the acoustic absorption of enhanced Porosity Concrete:http://cobweb.ecn.purdue.edu/~concrete/weisis/publications/journal/Rj017.pdf

Prokopski, G. & Halbiniak, J. 2000. Interfacial transition zone in cementitious materials. Cement and Concrete Research 30: 579-83.

Scholz, M. & Grabowiecki, P. 2007. Review of permeable pavement systems. Building and Environment 42(11): 3830-3836.

Yang, J. & Jiang, G. 2003. Experimental study on properties of pervious concrete pavement materials. Cement and Concrete Research 33(3): 381-386.

Zhuge, Y. 2008. Comparing the performance of recycled and quarry aggregate and their effect on the strength of permeable concrete. 20th Australasian Conference on the Mechanics of Structures and Materials, Toowoomba, Dec. 215-221.

Zaitsev, Y.B. 1983. Crack propagation in a composite material. Fracture Mechanics of Concrete 8:251–299.